Technical Survey and Forecast for Information Fusion

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"One of the greatest opportunities of the current Revolution in Military Affairs is to design and build computer networks that can enhance - and replace - humans in many aspects of the data 'fusion' process."

Admiral William Owens,

Lifting the Fog of War, Farrar Straus & Giroux, 2000.

ABSTRACT

This paper summarizes the results of a study forecasting the development of information fusion technology over the next 20 years [1]. The study was carried out on behalf of the Swedish Armed Forces, as part of an effort to estimate future developments in some technology areas of high relevance for the development of a Network-Based Defence system.

1.0 INTRODUCTION

Information fusion is still in the research stage and it is not yet clear how its basic methodology should be structured. The study describes the current situation based on a thorough and critical analysis of the open research literature. Based partly on published assessments by other authors, partly on the author's own experience, an estimate is then made of the likely progress in this area over a 10 and a 20 year period.

The combined effect of rapid technical development in sensor technology, the establishing of new communication technologies globally, and the literally exploding improvement of the price-performance ratio for computer systems, forms the technological background of the efforts by a growing number of nations to create a Network-Based Defence (NBD).

This move towards NBD implies that military decision makers will receive an ever increasing information flux to try to cope with. Information fusion is about providing support in the task of weighing together and interpreting this information, i e, to instantiate, perhaps even build, good models of a complex, uncertain reality more or less in real time.

New and rapidly improving capabilities to automatically collect large sets of data, and to move large sets of data across communication networks, have raised new questions regarding opportunities to automatically sort, classify, and interpret data to form an operational picture. In this process, data from various sources are used: sensor data, as well as data on probable behavioral patterns of the opponent, cultural and geographic characteristics of the area of operations, etc. Such data have previously been *fused* to an operational picture through time-consuming manual analyses and discussions. As the availability of sensor data explodes as a result of technological advances, this manual fusion process becomes a bottleneck when establishing the operational picture. If sensor data can not be processed and automatically

Paper presented at the RTO IST Symposium on "Military Data and Information Fusion", held in Prague, Czech Republic, 20-22 October 2003, and published in RTO-MP-IST-040.

Report Documentation Page

Form Approved
OMB No. 0704-0188

Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

1. REPORT DATE **00 MAR 2004**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**

4. TITLE AND SUBTITLE **Technical Survey and Forecast for Information Fusion**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Swedish Defence Research Agency FOI SE-172 90 Stockholm SWEDEN**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM001673, RTO-MP-IST-040, Military Data and Information Fusion (La fusion des informations et de données militaires)., The original document contains color images.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**UU**	**29**	

fused with information already known from other sources, the increased availability of sensor data in the widest sense will be of little use. Also, it is only through the use of computerized information processing that end users can be made to benefit from the quality, robustness, and conceptual precision of the methods being developed by information fusion research.

Like in other large-scale and ambitious applications of information technology there may exist a risk of user alienation if systems become too autonomous and do not communicate adequately with its users during the analysis and forecasting processes. This risk is closely related to an increasing need for a mathematical and scientific education of those intelligence officers who will be the users of future information fusion systems.

Table 1: General Forecast for the Development of Automated Information Fusion

Situation in 2002	Estimated situation in 2012	Estimated situation ca 2022
Immature technology. Methodological basis of information fusion not yet established.	Methodology for situation analysis developed for many military applications.	Effective systems for threat and situation analysis integrated in NBD.

2.0 TECHNOLOGY AND SYSTEMS FOR INFORMATION FUSION

Information technology – primarily software – supporting the task of creating in real time a correct situation description, or more precisely, model, adequate for the decision support needs of an operative or tactical military commander, will be called here *information fusion systems.* The concept covers those parts of the information fusion process which are intended to support analysts and decision makers in their planning and execution of intelligence collection, as well as their analysis, of intelligence from all sources, i e processes which are more closely related to intelligence processing than to sensor data processing or target position estimation.

The purpose of developing and deploying systems for information fusion in tactical C^2 and intelligence systems is thus to provide support to commanders and intelligence officers in their continuous work of collecting, processing, and conceptualizing information about various potential threats during an ongoing military operation. Sensors and multi-sensor systems have important roles as "subcontractors" in this process, however, in focus here is the issue of how to shape computer supported methodology for *real-time modelling*, i e, representation, estimation, interpretation, and forecasting of threat extent, structure, capability, and options, given what is known about the opponent's situation and behaviour, or doctrine, as well as the geographical environment. Note that the intent of the opponent will usually be unknown, even "unknowable", to the fusion system, whose task is instead to establish and evaluate all his options to act. The underlying idea is that from a sophisticated analysis and evaluation of these options using mathematical modelling, it should usually be possible to radically but rationally reduce the number of likely enemy actions to a small set, manageable by human decision makers, and whenever this is found not to be the case, to redirect in real time one's own intelligence collection resources so as to eventually reach that goal.

Reconnaissance and analysis resources, as well as fusion results such as situation and forecasting information, must be accessible from all levels in the operative organisation. In dialogue with its users, the system needs to be able to make good proposals to resolve resource conflicts as they occur. Also, it needs to function in situations when communications have low capacity, even when they are intermittent, although necessarily with reduced precision of its result. Thus, the feasibility of information fusion depends strongly on the availability of a seamless and flexible information network. Without such a

network, neither input to nor output from fusion processes will reach their destination in time. Quantitatively, the message delivery time and bandwidth of each link in the network at each point in time will be important factors influencing the total capability of the information fusion system.

3.0 INFORMATION FUSION TERMINOLOGY AND PROCESSES

Language usage in the fusion field has been and still is varying, so that there is reason to define the terminology used in this paper (and in the Swedish R&D community for NBD).

Sensor data fusion, or using a practical abbreviation, *sensor fusion*, deals with creating a target situation description (or "picture") based on data received from the sensors. Static data, such as sensor and target properties or threat libraries, are also sometimes used. Sensor fusion primarily involves target tracking, but also target identification based on sensor data. *Multi-sensor fusion*, in particular, denotes such sensor fusion where more than one sensor is employed to create target tracks or situation picture. The purpose of multi-sensor fusion is to combine information from several sensors in order to obtain greater robustness, precision, and range from the sensor systems. *Multi-sensor multi-target fusion* is sometimes used when one wants to emphasize the use of a set of several sensors to create and maintain a target situation picture containing many different perceived targets which may perhaps also appear and disappear randomly.

Information fusion employs, in addition to all available target information, other kinds of intelligence data, as well as other relevant kinds of data. This is all fused during *situation assessment* into a higher-level *situation model* (here too sometimes called "situation picture", a usage we have frequently found misleading). Interpretation of the situation – threat, vulnerability, tactics etc. – is performed in the *impact assessment* process. The *resource management* process provides feedback to the sensors as well as to the assessment processes. In our terminology, Levels 0 and 1 in the so-called JDL model do not belong to information fusion and should be viewed as sensor fusion processes.

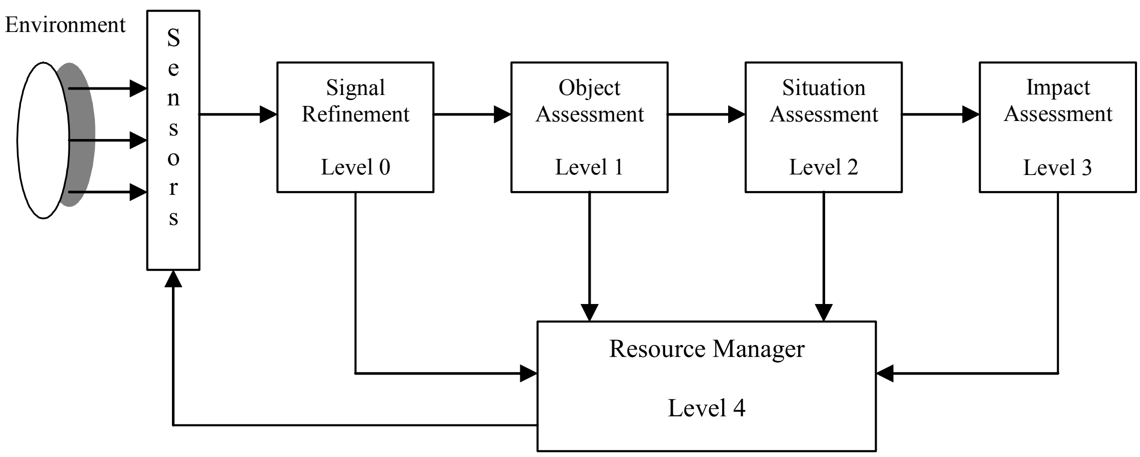

Figure 1: JDL Model.

3.1 Level 2: Situation Assessment

Results from sensor fusion processes (level 0 and 1) are passed to a decision support system for situation and impact assessment. During situation assessment a model is reconstructed of the situation which caused the observed data and events. A set of alternative hypotheses about the perceived situation is also

generated. The hypotheses are evaluated with respect to the observations and are ascribed probabilities. The goal of this analysis is to find, characterize, and rank the most likely hypotheses. Situation assessment is a chronologically ordered process where data arrive over time and the analysis is successively refined towards a gradually more detailed and probable best hypothesis.

3.1.1 The Aggregation Problem

If, like during situation assessment, one strives to understand an ongoing operational development, the relevant level of analysis is usually not separate physical objects but groups of organizationally related objects. Frequently, the goals of a military operation are such that no single unit is indispensable for completion of the task. Further, a group of platforms may present a different – and much greater – threat than the sum of all the threats presented by each individual platform. Thus, in addition to potentially meeting the need of the decision maker to have the situation presented in a way which avoids too much detail, aggregation of vehicles or other platforms to military units promises to be an important step towards the goal of unmasking the opponent's intent and find effective countermeasures.

The aggregation problem for sets of objects [2] has certain similarities to the classification and identification issues for single objects which are treated during object assessment. Based on observations of single objects (or, more accurately, of certain attributes of an object), one wants to deduce which kind of unit is observed. The difficulties are in some respects similar. How do you determine if two or more observations belong to the same unit (object)? What kind of a priori knowledge do you need to determine which unit (object) the various objects (attributes) belong to? How should this a priori knowledge be represented, how should the evaluation be carried out, and how do you best represent the uncertainty of the conclusions?

In the aggregation problem there is the added complication that unit types belong to some (usually hierarchical) organizational structure. Different objects may belong to different units, different units may belong to different companies, etc. Certain identification on one level may be combined with uncertain identification on another level. Also, the structures at each level are dependent of each other. Higher units may contain certain specific smaller subunits and at the same time some subunits may in themselves be organization-determining. Methods which can deal with such dependencies are therefore likely to be particularly interesting.

3.1.2 Level 3: Impact Assessment

Impact or *threat assessment* is a process which should be viewed from several perspectives.

Here risks and opportunities are analyzed for own forces to meet the opponent in an effective manner. Results from the previous situation assessment is combined with received indications about the opponent's intent as well as prestored information from technical and doctrinal databases to deliver a complete impact assessment.

In impact assessment possible threats are identified and ranked according to the character and time horizon of the threat. Until now, research has largely been focused on air and sea applications where the threat analysis takes its departure from own aircraft or ship survival. In simpler cases the threats from adverse forces are evaluated based on distance and speed of approach of the threat. Here one also needs to take the speed of own aircraft/ship into account. Doctrinal data play an important role. Knowledge about weapon systems and their ranges may help refine threat evaluation, and more complex doctrinal data on, e g, tactical behaviour might also be used in the modelling.

In a longer time perspective the threat analysis may be extended from dealing only with the security of the own unit to that of other targets of interest to the opponent. Here too doctrinal information about the

opposing units will play an important role, however, needs to be extended with geographical data about avenues of approach and trafficability.

To estimate the probability that a potential threat is real is a critical part of impact assessment. Potentially, each enemy unit present within a certain area a possible threat to any valuable targets in the area, but obviously certain combinations of units and threats are less likely. The generation of threat models therefore needs to be sensitive to, and provide a representation of, those factors which are likely to influence the probability assessment of various threats, such as distance to target, direction of movement, military strength and type of unit.

3.2 Level 4: Adaption and Resource Allocation

Multisensor systems become ever more important as a component in a number of applications, military as well as civilian. Since a single sensor can usually perceive only limited and partial information about its environment, one needs to make use of several coordinated sensors of the same or different types, to obtain sufficiently many comprehensive local views with different focus and from different perspectives, in order to create a complete, integrated view of a complex phenomenon [3]. This presumes that an underlying model of the observed phenomenon exists and may be exploited. The value of multi-sensor systems therefore consists in their ability to create greater opportunities for machine perception and to improve the perception of the state of the observed environment, compared to what could be achieved by a single-sensor system.

On a higher level, sensor management deals less with direct control in real time, although this functionality may well be desirable in the future, than how best to plan the use of (combinations of) mobile sensor platforms such as, e g, *Unmanned Aerial Vehicles* (UAV). The basic issues, however, remain the same: sensor resources are to some degree given, however, the information needs have to be defined. Here, impact assessment plays an important role. In the simplest cases the issue is how to cover a set of areas in the most efficient way. Since maybe not all areas can be covered certain areas will have to be prioritized with respect to current threat patterns.

In dedicated sensor systems resource allocation essentially consists of direct sensor control: how are sensors to be controlled in order to track a target or cover an area in the most efficient way. Basically, this is an optimization problem where sensor resources are weighed against information needs. Sensor resources are given, but the information need may be defined in different ways.

4.0 RESEARCH STRATEGY

The key research strategy issue in this context is to identify problem areas and specific research issues which can be tackled by a coherent methodology, and at the same time have, or can be expected to acquire, tactical, operative, or strategic relevance.

Although fusion methodology is of great interest in a number of application areas, we focus here on military applications. This characterization is however far from sufficient when addressing the question whether information fusion is a possible, respectively an important, technology in network-based defence. Those problems which may need fusion support during an international peace-keeping operation are different from those which need to be solved when defending against an armed attack on one's own territory. In another dimension, issues of strategic intelligence during peacetime are largely different from those which need to be answered at the tactical level in wartime. Applying information fusion to the defence of a country's infosphere is again different from information fusion applied to the forecasting of an enemy army unit's movements and intents.

This does not imply that there is no ground for considering all these problems as related, and by doing so, assigning the information fusion concept a broad, cross-disciplinary meaning. It does imply, however, that the technical forecast we are trying to produce has to be made with specific applications in mind.

Although it is obviously impossible in general to foresee with certainty what an enemy unit is going to do, on the other hand no commander of a ground-based unit has much flexibility to rapidly change the situation of his unit. The emergence of increasingly swift observation, command, and impact processes will therefore lead to an increased need for tools that can provide timely and accurate short-time predictions.

However, to be able to make longer-term forecasts than those purely kinematical and dynamical predictions which multisensor fusion provides, one has to exploit two complex scientific areas:

- quantitative, or in some cases qualitative theories for reasoning under uncertainty
- knowledge about those limitations which the environment and the organization and doctrine of the enemy impose.

5.0 HOW CAN INFORMATION FUSION BE AUTOMATED?

In *Handbook of Multisensor Data Fusion* [4], this issue is discussed by Hall och Steinberg.

5.1 Situation Assessment

Improved methodology for situation assessment, a central information fusion subject area, considered by these authors to be immature today, will probably require a better understanding of how to select and use existing methods for knowledge representation (like rules, frames, scripts, and fuzzy logic), in conjunction with a better appreciation of the strengths and weaknesses of human reasoning about such problems. One example is the need to employ reasoning based on negative information, i e information that has not been observed but should be expected in a hypothetical situation. Another promising area is considered to be development of tools for compensating known weaknesses in the way humans manage information (e g, humans often look for information which can confirm a stated hypothesis, rather than information that may refute it).

5.2 Impact (Threat) Assessment

Regarding methods and systems for impact assessment the situation is said to be similar but even more immature. The problem of predicting an opponent's intent is a basic issue in impact assessment, and it can be systematically modelled in many cases when the opponent's behavior follows a known doctrine. In modern wars and conflicts, however, doctrine is frequently poorly developed, unknown, or even non-existent.

Impact assessment is dependent on our ability to recognize behaviors, and furthermore requires methods for evaluating both enemy intent given a certain behavior, as well as for modelling one's own vulnerability against various kinds of threats. Since interpretation of threats and possibilities can seldom be made unequivocally, it is important to endow a system for impact assessment with the ability to represent and manage many alternative interpretations, all with some measure of likelihood attached. Here, one's dependence on doctrinal knowledge and behavioral rule systems is even greater than during situation assessment. This we consider to be one of the greatest obstacles against the development of methods that can be applied across a wide spectrum of unconventional threat scenarios. It is likely, e g, that new methods must be created for mapping, and later perhaps modelling, of organizational structure and threat behavior of terror and guerilla organizations.

5.3 Process Control

Process control involves, e g, methodology which has long been applied to controlling single sensors and homogeneous sensor systems. In information fusion the concept has a wider meaning, however: how can the entire intelligence collection process be optimally controlled in real time? In this area, there is much work left to do, although significant progress can be expected also in the shorter term.

6.0 FORECAST

Our own view of the state of development in the areas of situation and impact assessment differs in a few but presumably significant respects from the one presented in the cited paper by Hall and Steinberg. An important recent trend has been the emergence of new theoretical approaches, creating significantly better opportunities for managing uncertainty and ambiguity in information systems. In general, new representation and analysis methods from the discipline called management of uncertainty are appearing more or less continuously, some of which, e g Bayesian Networks and Abstract Hidden Markov Models, promise to be effectively applicable to information fusion problems, such as multi-agent plan recognition [5].

In particular, we believe that new developments in finite set statistics, new particle filtering methods, and clustering methods for force aggregation, in combination with new methods for multisensor management, advanced simulation systems and terrain models, will lead to important advances regarding detection, classification, tracking, and prediction of complex set objects, such as ground forces on various organizational levels. In light of these and other scientific advances, our assessment can be considered somewhat more optimistic than that of Hall and Steinberg.

We believe that the problems that primarily have to be solved to enable significant automation of information fusion processes are in large measure scientific methodology issues about how to formulate, model, and solve certain generic problems, whose structure is often currently insufficiently known. If one recognizes this, it becomes easier to understand why research in this area will require considerable resources, including probably calendar time, before practical results can be obtained across a broad application area.

In conclusion, we estimate that within ten years there will exist methodology for information fusion which will be useful in practice for the Swedish defence, in particular for situation assessment in ground warfare scenarios, and that an additional 10 years of focused research may lead to the establishing of effective, productivity-boosting such systems within the context of a network-based defence. This prediction presumes that the quality and quantity of this research does not diminish but instead successively improves during the next 5 to 10 years.

ACKNOWLEDGEMENTS

The author is indebted to Egils Sviestins, SAAB Tech Systems, John Cantwell, KTH, and Johan Schubert, Swedish Defence Research Agency (FOI) for oral and written exchanges which have strongly influenced the views presented in this paper.

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The need for information fusion automation

Networked sensor and communication systems can generate intense information flows and will change commander's main concern

- from managing the "the fog of war", i.e., *vague* and *incomplete* information
- towards interpreting and understanding of great amounts of complex information under *severe time constraints*

Automating information fusion is therefore a critical research task in the quest for information superiority

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What is (tactical) information fusion ?

- information fusion exploits
  - available tactical intelligence information
  - information about the environment
  - known properties of the opponent's platforms, combat units, organisation and doctrine

- to dramatically improve speed and accuracy of assessing and predicting the opponent´s capabilities and intent

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Information fusion subprocesses (JDL)

- *situation assessment*, e. g., instantiate a relevant and adequate *situation model of a tactical situation*
- *impact assessment*, e. g., evaluate situation and predict *possible consequences of decision options*
- *process refinement*, e. g., use situation and impact assessments in combination with models of information collection capabilities to *find and execute near-optimal collection schemes*

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Where can information fusion be used...

- in *interpretation* of observations:
  - position and timing estimation
  - classification of objects and systems
  - identification of objects and systems
  - correlation of observations dispersed in time and space
  - aggregation to systems from observations of components

...Where can information fusion be used?

- in *assessment* of the enemy's potential courses of action:
  - probable time and place for engagement
  - estimation of the enemy's fighting capability
  - estimation of relative strengths
- in *combination* of information from different sources, including databases, sensors, and humans
- in *optimization* of the intelligence collection process

Current situation in information fusion (following Hall & Steinberg, 2001)

- many prototype systems have been developed, most of them restricted to situation assessment
- KBS technology has dominated

Variants include:

- blackboard systems
- systems based on logical templates
- case-based reasoning systems

Emerging use of fuzzy logic and agent-based systems

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Situation assessment, current limitations

- few and limited operational systems
- experience lacking from upscaling prototypes to operational systems
- very limited cognitive models
- unsystematic testing and evaluation, on model problems only
- no widely accepted technology exists for knowledge management

Impact assessment, current limitations

- doctrine specific, brittle systems
- few and limited operational systems
- experience lacking from upscaling of prototypes to operational systems
- quantifying intent is a difficult problem
- models require known and established enemy doctrine
- quickly changing situations are difficult to model

Process refinement, current limitations

- hard to take mission constraints into account
- scalability problems for adaptive systems with many sensors
- difficult to use non-commensurable sensors optimally
- very difficult to tie sensor management to human information needs

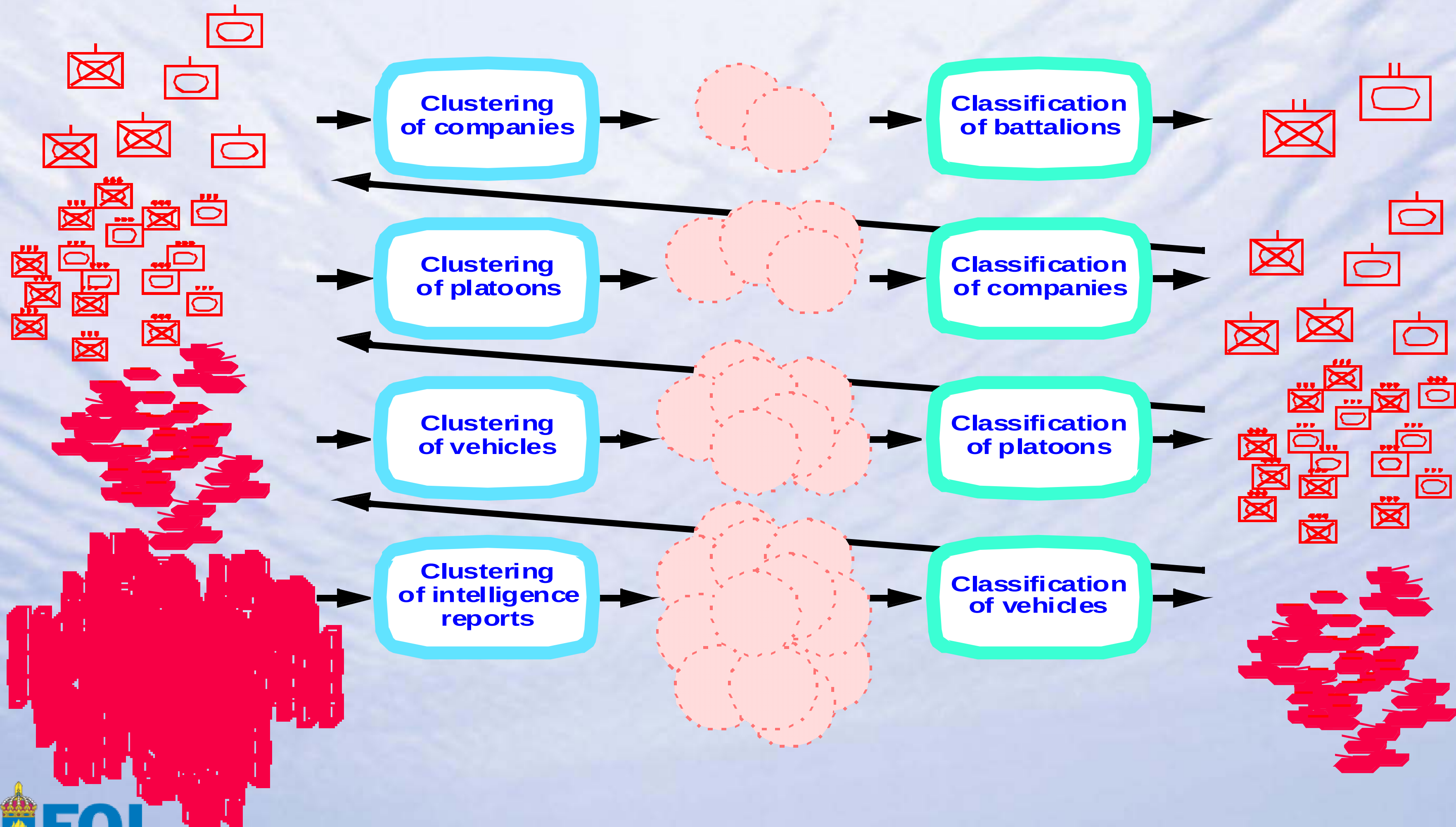
Can we see some progress?

- in situation assessment: systematic uncertainty management (*random sets*, *Dempster-Shafer theory*), use of general tracking concept in *force aggregation* and *group tracking* problems
- in impact assessment: new simulation methods, e.g., *ANTS* for determining and evaluating *avenues of approach*, *dynamic Bayesian networks* in *plan recognition* and *intent assessment* (*R. Suzic*, this conference)
- in process refinement: game theory-based *negotiation* to support cooperative use of possibly non-commensurable sensors

What is force aggregation?

- in *situation assessment*, the task of estimating the composition and structure of an enemy unit from:
  - a set of observations of objects belonging to the unit
  - a priori knowledge about doctrine (materiel, organisation, behaviour)
- several approaches are possible; FOI has worked particularly with methods based on *Dempster-Shafer clustering*

Force aggregation as clustering + classification



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What is tracking *really*? (N. Gordon & al)

- tracking uses models of the real world to be able to *estimate the past and present and predict the future*
- this is achieved by extracting underlying information from an *incoming stream of noisy/uncertain observations*

Any extraction of information from a *time evolving system* is a tracking problem; tracking applications are innumerable.

Only recently, general tracking algorithms, based on *particle filtering*, have become available.

Two military tracking challenges

- **estimate, in the presence of clutter and physical obstructions, using spatio-temporal environmental cues, which objects are present in an area of interest, where they are now and how they moved there (*situation "picture"*)**
- **identify and track units on higher organisational levels (sets of objects), combining the problems of *tracking*, *aggregation,* and *identification* (*tactical intelligence acquisition*)**

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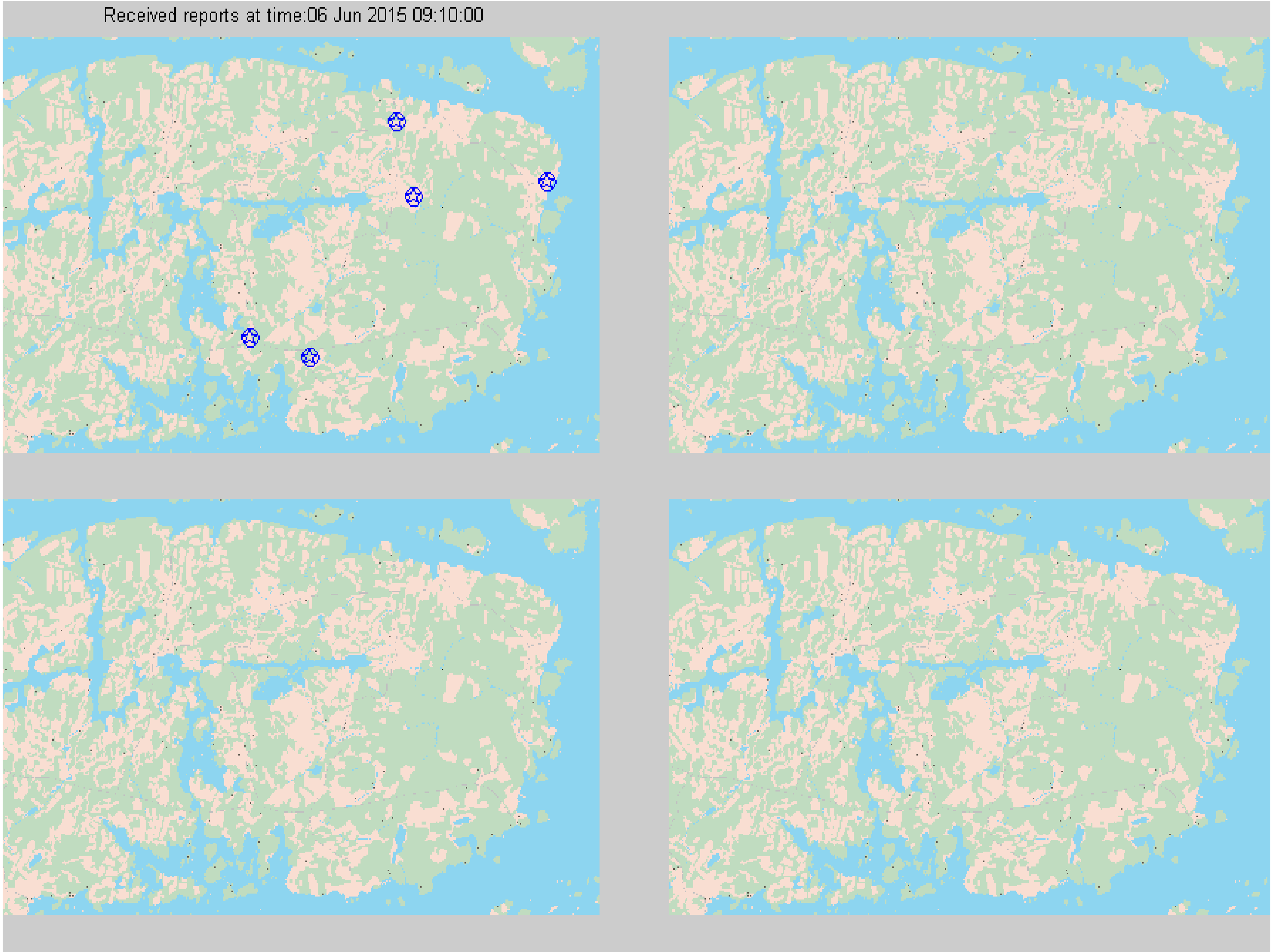
Example: sketchy preview of FOI's IFD03

- Systematic architecture based on simulation framework
- Human observers and UAVs make uncertain detections and report to a remote command center
- Command center starts a particle filter tracking module, which is continuously updated by new reports
- Reports are aggregated to vehicles, then to platoons
- 4 views:

Sensors with their reports	Clustered reports: vehicles
Clustered vehicles: platoons	Particle filter output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Fusion of reports in IFD03…

- reports are *clustered* using Dempster-Shafer clustering techniques
- the *force aggregation service* generates aggregation results based on available sensor, terrain, and doctrine information
- lower units are aggregated to higher and are classified whenever sufficient information is available

...Fusion of reports in IFD03

- the *particle filter terrain tracker service* is exploited by the *sensor resource manager* to allocate and focus available sensor resources
- when an aggregation result (unit) has been created, it is passed to the particle-filter-based *group tracker*, which repeatedly reports the unit´s position and speed

Automatic information fusion - opportunities

- any sweeping claim that information fusion will be capable of automatic prediction of enemy actions is *nonsense*
- however, in properly delimited frameworks, behavioral simulation models based on robust uncertainty management methods may be systematically fused with observations to form useful predictions
- so, application of *systematic uncertainty management* methodology to *well-specified military situations* will likely create new opportunities for generating and evaluating decision alternatives

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Conclusion and forecast

- well-established sensor fusion methods can rarely be used on a tactical intelligence level
- however, via formulating and solving a ”critical mass” of concrete problems using systematic methodologies and measures of effectiveness, a simulation-based *technology for information fusion* is likely to be created in the next ten to fifteen years
- reasonably complete, deployable systems will be developed based on such technology
- hard architectural, logistical, and organisational issues need to be addressed for IF systems to be successful